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SOLAR MAGNETOMETRY WITH THE DUTCH OPEN TELESCOPE

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ABSTRACT

The Dutch Open Telescope (DOT) has become operational at the Roque de los Muchachos Observatory on La Palma. The first image sequences taken with this innovative telescope demonstrate its capability for tomographic high-resolution imaging of the magnetic topology of the solar atmosphere up to the transition region over the large field of view permitted by consistent speckle restoration. We review the science needs for such imaging and describe the DOT solution to the problems posed by the earth atmosphere and the solar physics niche filled by the DOT.

Keywords: solar telescopes, solar atmosphere, solar magnetism, speckle reconstruction.

1. INTRODUCTION

This meeting connects solar physics with the terrestrial climate. One back-reaction aspect of the latter on the former is that terrestrial weather, in particular the "atmospheric seeing" which characterizes the amount of image deterioration caused by the earth's atmosphere, is of great importance in setting the angular resolution of groundbased solar telescopes. Achieving high angular resolution over long durations in many spectral diagnostics is a prime quest of solar physics because many of its key problems are dominated by magnetism while the solar magnetic field is structured into very slender tubes and loops. The latter harbor important processes especially in the outer solar atmosphere where magnetic pressure dominates gas pressure, but mapping them and measuring their properties requires higher resolution than achieved sofar due to the spoiling by the earth's atmosphere. The quest is to obtain high angular resolution not just in the brief glimpses permitted by the best seeing at the best sites, but consistently over long duration. At present, this goal comes in reach with the advent of adaptive optics. The Dutch Open Telescope described here relies on an alternative technique to get rid of the degradation by the earth's atmosphere: consistent high-volume speckle restoration. Its advantage is that it produces image restoration to the diffraction limit over the whole field of view of the telescope.

In this contribution we briefly review the reasons why high angular resolution is so important to solar physics and describe how the new and innovative Dutch Open Telescope (DOT) fills this need by speckle-restored multi-wavelength imaging. This presentation is in rather general terms in view of the mixed audience at this conference. More detailed DOT presentations were given at the 20th NSO/Sac Peak Summer Workshop and will appear in the ASP Conference Series (editor M. Sigwarth). An excellent recent monograph on solar (and stellar) magnetism that is suited as introduction to scientists from outside the field (such as climatologists) is *Solar and Stellar Magnetic Activity* by Schrijver & Zwaan (2000).

2. HIGH RESOLUTION SOLAR PHYSICS

Figure 1 updates a figure printed in older ESA proceedings (Rutten 1993). The update consists of tilting the dotted groundbased resolution limit to vertical. The image-restoration revolution, whether through adaptive optics or speckle reconstruction, will permit groundbased registration of solar scenes at about 100 km resolution over durations as long as the sun shines (or round the clock with round-the-earth networks). The tilt change implies a much better grasp on sunspot umbrae and penumbrae, "magnetic grains" which mark individual fluxtubes away from active regions, and prominences. These are all magnetically dominated structures that are rather ill-understood. The phenomena more to the left in Fig. 1 are mostly gasdynamical in nature and are generally much better understood, in particular the granulation (turbulent convection) and the 5-min oscillation (global *p*-mode oscillations). The MHD paradigms (capitalized in Fig. 1) are applied elsewhere in astrophysics (*e.g.,* to explain accretion disks around magnetic white dwarfs and neutron stars and the AB Dor and Be star phenomena), but they depend on high-resolution solar physics for elaboration. Likewise, the sun–climate connection requires identification of the way in which the sun modulates its irradiance and wind, *i.e.,* to understand the activity cycle. The major cycle components, active regions and magnetic network, are made up of the slender MHD configurations called fibrils and fluxtubes. Studying solar cycle properties entails trying to understand these basic building blocks of magnetism in the solar atmosphere at their intrinsic scales and their pattern evolutions over long durations. The currently achieved tilting of the groundbased limit in Fig. 1 therefore represents a major breakthrough in solar astrophysics.

3. TOMOGRAPHIC SOLAR PHYSICS

Another requirement in solar physics is a holistic approach, as exemplified by the SOHO mission ("from the solar interior to the outer heliosphere"). In optical solar magnetometry, one aspect is the need to sample the solar atmosphere at different heights simultaneously. The reason is that the solar atmosphere changes dramatically between different regimes and presents drastically different scenes to the terrestrial observer at different wavelengths.

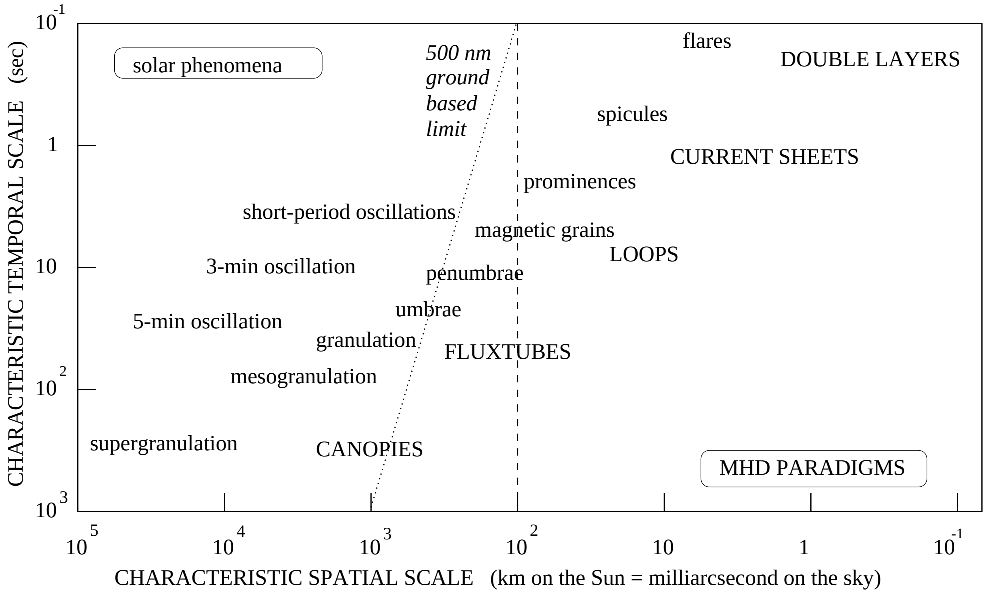

Figure 1: Spacetime characteristics of solar phenomena (small print) and solar-inspired paradigms of magnetohydrodynamics (capitals). The dotted groundbased limit corresponds to the best "seeing" of the earth's atmosphere which even at the best sites permits subarcsecond resolution only over brief duration. The limit now tilts to the dashed vertical line set by aperture diffraction, thanks to the advent of adaptive optics and speckle restoration. The latter technique is exploited at the DOT.

The solar photosphere, defined as the layer where the bulk of the electromagnetic radiation escapes as visible light (a dramatic transition from near-equilibrium photon enclosure, killing off the subsurface convection into the shallow pancake pattern called granulation) is also the layer where magnetic fields take over from gas dynamics in dictating the structuring and in supplying the key processes, and it is also the outermost layer where the sun may be regarded as spherical in zero-order approximation. The chromosphere is magnetically split into network and internetwork in quiet regions and is very finely structured above active regions. The transition to the corona consists of tiny fibrils with much variation in length, inclination, and ordering. The closed-field parts of the corona outside coronal holes are made up of bundles of very thin coronal loops. Yet unidentified processes supply energy to the gas in these loops, reaching a balance against cooling by X-ray photon losses at temperatures of 1–2 million K.

The loops are magnetically anchored (in unknown fashion) to the strong-field fluxtubes that break out of the photosphere and respond dynamically on a wide variety of timescales to the footpoint forcing. These magnetic connections between very disparate regimes, from gas dynamics via magnetohydrodynamics to plasma physics and from LTE radiation enclosure to X-ray photon drain, require simultaneous study of structures, processes and radiation in the photosphere, chromosphere, transition region and corona.

4. PROXY MAGNETOMETRY

The Dutch Open Telescope (DOT)[1] relies on "proxy" magnetometry, *i.e.,* using the intensity encoding imposed by magnetic structures to portray the topology and evolution of the magnetic field. The chief optical diagnostics are the G band, Ca II K, and Hα. Higher up, the coronal topology is best sampled in soft-X ray lines such as the Fe IX, Fe X line pair at 171 nm used by the TRACE mission[2] to produce vivid movies of coronal field evolution. Obviously, holistic solar tomography requires combining groundbased observing and space observing — a tactic frequently followed in current solar physics, for example in the multi-telescope campaigns of the European Solar Magnetometry Network (ESMN)[3].

4.1 G band: photospheric topology

The G band around 430.5 nm (a 1 nm piece of spectrum filled with lines of the CH molecule, the name was given by Fraunhofer) has been found to be the best diagnostic to chart the location and evolution of magnetic fluxtubes in the deep photosphere because these appear on high-resolution G-band filtergrams as bright points (Fig. 2). Standard fluxtube models explain this from the "hot wall" effect (Spruit 1976, Spruit & Zwaan 1981): the tube is relatively empty because the inside magnetic pressure balances the outside gas pressure, and so it acts as a viewing tube through which radiation escapes from layers below the outside surface, with the hot tube walls producing brighter emission than the surroundings. In the G band this contrast is enhanced because the

[1]DOT: http://dot.astro.uu.nl
[2]TRACE: http://vestige.lmsal.com/TRACE
[3]ESMN: http://www.astro.uu.nl/∼rutten/tmr

CH molecules dissociate in the fluxtube so that the many dark CH lines in the G band vanish and the tube gas gains even more transparency compared to the outside gas than at other wavelengths.

The intrinsic sharpness of the photospheric fluxtubes is very high because they are very thin and the G-band photons are emitted thermally and are not much spread by scattering on their way out. At 100 km resolution most resulting G-band bright points are not resolved, but at least they are identifiable so that they can be located and traced in time. At somewhat lower resolution (say 0.5 arcsec) they vanish because they are mostly located within dark intergranular lanes so that smearing by atmospheric seeing cancels bright against dark (Title & Berger 1996).

4.2 Ca II K: chromospheric topology

The Ca II K line is the strongest Fraunhofer line and samples the chromosphere at about 1000 km above the white-light surface. At this height, the magnetic network is enhanced by yet unidentified heating processes so that the Ca II K line-center intensity (at about 0.1 nm bandwidth) provides an excellent magnetogram proxy (but unsigned). This fact has been exploited extensively in gauging the magnetic activity of sun-like stars (reviewed extensively by Schrijver & Zwaan 2000).

The sharpness of Ca II K images is intrinsically less than for the G band, partially because the line photons are scattered considerably on their way out before their final escape towards the observer, and partially because the fluxtubes expand and merge with height. The same regime and the same patterning are also sampled by imaging in the near-UV continua, but the state of the art (160 nm and 170 nm passbands of the TRACE mission) does not yet reach the intrinsic angular resolution nor the resolution obtained at groundbased telescopes.

4.3 Hα: transition region topology

The Balmer Hα line comes from the most abundant element but is much less strong than Ca II K in the solar spectrum because its lower-level $n = 2$ population has very low weight in the Boltzmann population partitioning over the hydrogen energy levels. Nevertheless, its high excitation energy causes this line to respond to gas at high temperature so that it maps low-lying fibrils in the transition regime between chromosphere and corona if these are sufficiently dense.

This transition regime has often been modeled as a spherical shell between the 8 000 K chromosphere and the 2 million K corona, but a high-resolution Hα movie immediately shows the fallacy of such modeling by displaying a mass of fibrils with no semblance of sphericity. The "moss" phenomenon discovered with TRACE indicates that 2 million-K plasma actually descends down to between the Hα fibrils in plage (Berger et al. 1999).

Using Hα as magnetograph proxy to derive the field topology from the observed fibrils is not straightforward because the latter harbor length-wise flows that modulate the apparent fibril contrast through substantial Dopplershifts. The resulting mix of brightness and Dopplershift variations requires full profile modeling, so that filtergrams must be taken at a number of wavelengths and interpreted through inversions based on sophisticated radiative transfer modeling.

The intrinsic Hα resolution can be exceedingly high because the fibrils may be effectively or even optically thin, imposing their scale on the emergent radiation without transfer smearing. This is particularly the case in filaments and prominences (the latter are filaments seen off-limb where the background radiation along the line of sight vanishes). These amazing structures, keeping very cool gas up in the hot corona and persisting very long, are rich sources of MHD physics. They probably consist of very thin magnetic fibrils in complex topologies that are best encoded in Hα radiation.

5. DUTCH OPEN TELESCOPE

The DOT is located at the Roque de los Muchachos Observatory on La Palma which is one of the best sites known worldwide for high-resolution solar imaging. The La Palma seeing can be superb, especially when the oceanic trade wind blows strongly upslope from the North. The photographs in Fig. 3 illustrate that the DOT adheres to its name in being open, a design which capitalizes on the strong-wind good seeing by firstly not upsetting the laminar character of the trade wind (open transparent tower), secondly by relying on mirror and telescope flushing by the same wind to avoid internal seeing. Solar heating of the prime focus structure is avoided by reflecting most of the image away with a mirror that is water-cooled to ambient temperature. The DOT design departs radically from all other high-resolution solar telescopes, which all employ telescope evacuation to avoid internal turbulence. The excellent image quality achieved by the DOT (Fig. 2 and assorted movies at http://dot.astro.uu.nl) attest to the success of the open principle.

One potential problem of an open telescope that relies on wind flushing is shake by wind buffeting. The DOT has an extraordinary stiff structure and sophisticated self-aligning gear trains that avoid telescope pivoting under variable wind loads. The DOT support tower is not stiff but permits platform motions only parallel to the platform, without the pivoting that would represent pointing errors when observing the sun (a source at infinity).

The DOT enclosure is a fold-away clamshell canopy of stiff fabric on heavy steel ribs. It can be closed in very strong winds and should withstand hurricane wind loads — and has done so the past winters. The coated fabric also tends to resist ice deposition, otherwise a major problem at the Canary Island mountain summits where undercooled fogs of-

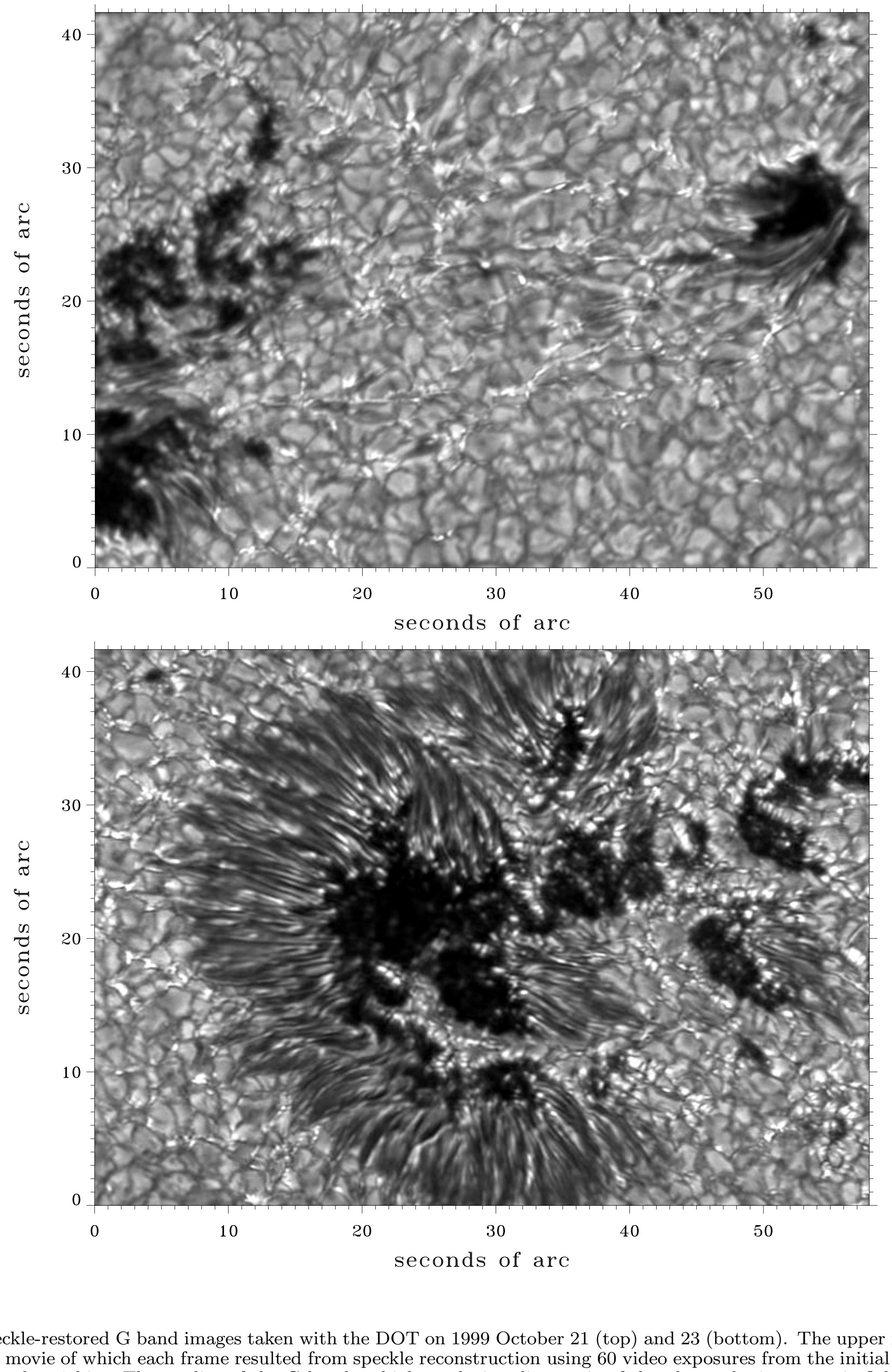

Figure 2: Speckle-restored G band images taken with the DOT on 1999 October 21 (top) and 23 (bottom). The upper image is part of a one-hour movie of which each frame resulted from speckle reconstruction using 60 video exposures from the initial analog DOT camera digitized at 8 bits. The quality of the G band as high-resolution diagnostic of the photospheric magnetic field topology is well exhibited: all bright grains in the intergranular lanes between the two sunspots correspond to strong-field fluxtubes that jut through the surface like angler's floats. The full movie is available at http://dot.astro.uu.nl and vividly displays the rapid evolution of the fluxtube patterning, with some tubes traveling fast from left to right and others the other way (rather as if pulled along by subsurface trout). The lower image shows a similarly complex scene including a larger sunspot.

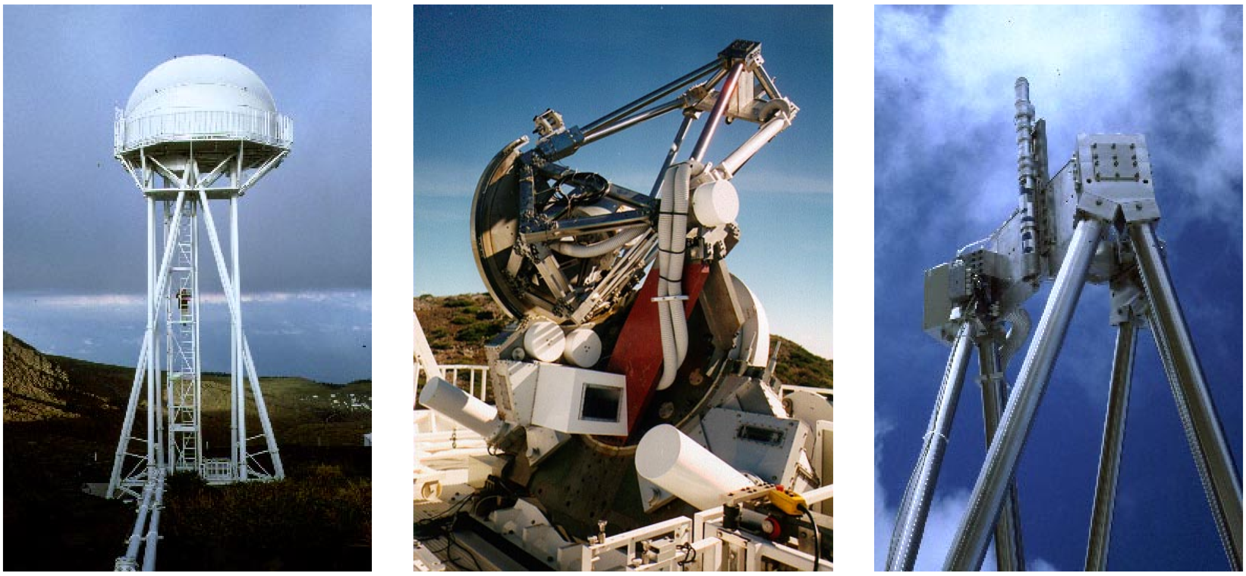

Figure 3: The Dutch Open Telescope at the Roque de Los Muchachos Observatory on La Palma. First panel: DOT with clamshell dome closed. The open tower is 15 m high. The pipelines in the foreground connect the DOT to the Swedish solar telescope building from which the DOT is operated, with fiber-optic links for image transport. North is to the right. Middle panel: DOT pointed towards the sun. The parallactic mount has large and heavy gears to avoid windshake since good seeing often correlates with strong wind on La Palma. The wind also flushes the primary mirror (45 cm diameter) which sits left of the two hoses. Righthand panel: initial prime focus instrumentation. The steel struts support imaging equipment that in this 1999 photograph consisted only of the slender tube at center, containing a water-cooled field stop (a 2 mm hole in a tilted mirror) which transmits only a 3 arcmin field and reflects the rest of the prime-focus image away, and re-imaging optics, G-band filter and a simple analog video camera of which the output is digitized at only 8 bits. At present, the DOT is being equipped with a new 10-bit digital five-camera system and multiple-wavelength optics that will mostly be mounted besides the incoming beam.

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The DOT is currently being equipped with a multi-wavelength multi-camera imaging system, using five digital CCD cameras to obtain speckle-restored images in the G band, the center of the Ca II K line, and a rapidly switched narrow passband in Hα using a birefringent Lyot filter on loan from the Canadian Research Council. Another tunable birefringent filter on loan from colleagues at Irkutsk will probably be installed to obtain Dopplergrams (velocity maps) using the narrow Ba II 4554 resonance line. The cameras will be operated synchronously in speckle mode (many-frame bursts at fast cadence) and provide a four times larger field of view than the one in Fig. 2.

6. SPECKLE RESTORATION

The DOT is located at an excellent site which provides the good seeing at strong wind combination that is needed to make the wind-flushed open telescope principle work. The DOT doesn't spoil the good seeing there by virtue of its open structure. Nevertheless, the site and the open principle do not suffice to tilt the groundbased limit to the vertical as in Fig. 1. Excellent seeing not only occurs fairly rare even at La Palma, but it also comes intermittently. Thus, the remaining atmospheric deterioration of the image quality limits the frequency and the duration of high-resolution image taking severely. The DOT answer to this problem is to consistently apply speckle reconstruction to all image acquisition. This sets the DOT apart from the atmospheric restoration programs elsewhere which rely on adaptive optics. Both techniques require at least moderate seeing quality because the solar scene should yet contain sufficient angular structure to permit gauging the atmospheric wavefront deformations. The gain is that moderate seeing occurs far more frequently as well as far more consistently over long durations.

Speckle reconstruction through the speckle masking technique is a well-established technique also in solar physics (Weigelt 1977, Weigelt & Wirnitzer 1983, de Boer & Kneer 1992) but has not been applied at the scale on which the DOT will employ it, generating up to 500 Gbyte of speckle data per observing day. This data stream implies that the (very small) DOT team will be swamped, but the hope is that in the near future parallel processing of the speckle data can be realized to obtain fast, perhaps near-real time, reduction.

The major advantage of the choice for speckle reconstruction over adaptive optics is that it delivers diffraction-limited resolution of 0.2 arcsec over the whole field of view set by the camera chip size, 130×100 arcsec^2 for the new DOT cameras. The alternative, adaptive optics, delivers full correction only for the central isoplanatic patch of about 5×5 arcsec^2 instead of the many hundred patches restored at the DOT. Multiconjugate adaptive optics (Beckers 1989) may solve this problem eventually, but not soon.

The reason that adaptive optics is intensely pursued at many other solar telescopes is that speckle reconstruction gives out at larger aperture because the speckle coding signal diminishes, and that adaptive optics permits feeding spectrometer slits with a stabilized image and so permits the long exposure times needed for spectropolarimetry at high spectral resolution and large signal-to-noise as required for precise Stokes vector mapping. Similar signal-to-noise problems may arise for the narrow-band imaging through the tunable Hα and Ba II 4554 filters at the DOT (or for future Fabry Perot instruments at the DOT), but these are solvable using the two-channel speckle restoration technique of Keller & von der Lühe (1992) in which synchronous wide-band speckle bursts define a deconvolution operator for the narrow-band speckle frames.

7. DOT NICHE AND PROSPECTS

With its new five-camera system and its large-volume speckle data-acquisition system, the DOT will be the first solar telescope with the capability to provide long-duration image sequences at the telescope diffraction limit (0.2 arcsec) that map the magnetic topology over a sizable field (130×100 arcsec^2) in tomographic fashion, simultaneously for the photosphere (G band), chromosphere (Ca II K) and low transition region (tuned Hα). Obviously, this capability fills a niche in solar physics concerning the horizontal topology and vertical structure of solar magnetic fields. It is also obvious that such tomographic high-resolution imaging will be desirable as context information to high-resolution spectropolarimetry at other telescopes employing adaptive optics, and to coronal field mapping using X-ray image sequences from space.

Whether the DOT will actually fill this niche is primarily a question of funding. The DOT team is very small (just the author list to this contribution) and the DOT finances are insecure. The current funding ends by the end of 2001. The DOT future therefore hinges on the first campaigns with the new multi-wavelength imaging system. In a wider context, the future of solar physics at Utrecht rides on the outcome as well.

8. DOT SPINOFF

The success of the DOT in obtaining superb image sequences (Fig. 2) even with the very simple initial analog camera (Fig. 3) has demonstrated the validity of the open concept. This demonstration and the advent of adaptive optics together open the way for much larger solar telescopes. Vacuum reflectors and refractors are limited to about 1 m diameter because the entrance window or lens cannot be much larger when thin, or causes resolution deterioration from imperfections in the glass volume when thick. The success of the open principle is therefore very good news. In addition, adaptive optics now permits restoration of the atmospheric degradation beyond the aperture limit at which speckle reconstruction (and phase-diverse reconstruction, or a mixture) work well. Thus, the future for high-resolution observing of the sun from the ground has become rosy. Two major new telescope projects exploit these advances. The German GREGOR[4] project aims to refurbish the Gregory-Coudé telescope at Izaña (Tenerife) with a new open feed on the top of the building, weather-protected by an upsized copy of the DOT clamshell canopy. The US solar physics community led by the National Solar Observatory is embarking on the ATST[5], currently targeted as an open telescope with 4 m diameter. Its roadmap advertises the DOT as technology example.

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